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ABSTRACT

Trains passing through tunnels cause noise and vibrations that negatively affect nearby residents. Developing a model to effectively predict ground-borne noise in nearby buildings faces challenges in the early project phases due to limited available data. This study suggests a framework for three stages based on precision and available information: location stage, planning stage, and construction stage. The first two stages correspond to determining the location and designing the railway track. The third stage involves the construction of the railway tunnel where more detailed information may be acquired by measurements on site. The prediction model presented here is formulated as a source term and correction terms considering train type, track type, track treatment, train speed, distance attenuation, foundation coupling, and floor-to-floor attenuation. Moreover, instead of using safety factors, which may cause an unnecessary increase in project costs, the concept of combined uncertainty is applied here, using the estimated standard deviation of each term and the root sum of squares. Consequently, a comprehensive ground-borne noise prediction model adapted to various stages and handling uncertainties is proposed.

1. INTRODUCTION

Trains passing through tunnels emit noise and vibration, significantly impacting nearby neighborhoods. A healthy community demands a thorough understanding of railway noise sources [1, 2], the ability to predict noise and vibration levels arising from railways [3, 4], and

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effective strategies for reducing generated noise and vibrations [5, 6]. This study focuses on developing a ground-borne noise prediction model for railway tracks within tunnels. Such a model is crucial for efficiently identifying effective treatments to reduce noise levels. Various models have been developed for the prediction of ground-borne noise, ranging from empirical methods [7, 8] to computational models such as three-dimensional finite element modeling and machine learning [9, 10]. Additionally, building acoustics theory and parameters like radiation efficiency have been employed to predict ground-borne noise within structures [11]. Hybrid models [12, 13] and artificial neural networks [14, 15] have also been investigated to predict ground-borne noise. Using these models requires detailed information about the site. However, in the early stages of the project, when the site location is not decided yet, it is challenging to make an accurate prediction. The accuracy of prediction models greatly depends on available data. This study introduces a three-stage framework based on the precision of available information suitable for each phase of the project: the location, planning, and construction stages. In the location stage, the model suggests simplified and single values for prediction. However, in the planning stage, the model is formulated in 1/3-octave bands.

This study aims to develop a model and methodology for predicting ground-borne noise generated by underground tunnels in Swedish bedrock conditions. The frequency range of interest is up to 1 kHz since Swedish bedrock without significant cracks can carry ground-borne noise at relatively high frequencies. Trains moving within underground railways induce vibrations in the rails and the track structure beneath them. The vibrations propagate through the surrounding ground, including rock and soil. Various factors influence the vibration level during propagation from a tunnel to a building, including factors related to the source term [16], propagation path [17], and receivers [18]. Each stage of the proposed framework considers multiple factors in predicting ground-borne noise levels, such as train type, track type, track treatment, train speed, distance attenuation, foundation coupling, and floor-to-floor attenuation. Each of these parameters adds uncertainty to the model. Some models [19] consider safety factors to deal with uncertainties, which may raise the cost of the project. There have been empirical models [20] developed to predict ground-borne noise, but few studies examine the statistical approach to deal with uncertainty. In this study, the sound pressure level in the room is estimated using the uncertainties of each term.

This paper is divided into the following sections. In section 2, the model and methodology is described. In section 3, the results are presented and discussed. In section 4, final comments and conclusions are presented.

2. METHOD

This study used existing knowledge and carried out measurements to develop a ground-borne noise prediction model for underground tunnels. Different measurements were taken to build the model: 1) Vibrations were measured in the Gårda tunnel and the Åsa tunnel in Sweden to estimate the source term of the noise for different train types; 2) Measurements inside two houses directly above the Gårda tunnel to calculate transfer functions; and 3) Measurements in a multistory building to see how vibration changes when traveling through various floors. The Gårda and Åsa tunnels have double-sided ballasted tracks and are built in bedrock. To measure the vibration levels in the tunnels, transducers were mounted on the tunnel wall horizontally (normal to the tunnel wall) and vertically (parallel to the tunnel wall). Several positions on the tunnel wall were used to ensure good coverage of vibrations. A total of 3000 passages were measured, including both passenger and freight trains in both tunnels. Sound and vibration measurements were conducted inside two houses above the Gårda tunnel. House measurements comprise a microphone to measure sound pressure level, a seismometer placed on the room floor to record vertical vibrations, and two seismometers on the foundation to capture vibrations in both horizontal and vertical directions. Additionally, to determine how the vibrations change when transferring from one floor to another, measurements were taken in a multistory building. Seismometers were placed vertically on the floors. The measurements were conducted using a hydraulic hammer operating during the construction of a nearby tunnel as the source.

2.1. Framework

In the early stage of a project, predicting ground-borne noise is difficult due to insufficient detailed information. A framework made up of three main stages is proposed. They are called the location stage, the planning stage, and the construction stage. The first two stages focus on finding the best site and planning the railway track carefully. At the third stage, more detailed information may be obtained during construction. In this way, a flexible and thorough approach can be implemented to predict and manage noise from the ground. The stages are described as follows.

Location stage. The location stage is utilized at the early stages of project development where few input parameters are available, such as railway system type, train characteristics, geotechnical conditions, and building sensitivity. The model at this stage can be used to choose the best site from several options. Typical and simplified values can then be used for the terms. At this stage, the model employs single numbers.

Planning stage. The planning stage is used at the design stage when more input data is available. Models developed in the planning stage provide more accurate quantification of vibration levels and precise location identification along the railway than those developed in the early stages. The precision of the result will be higher at the planning stage and parameters formulated in 1/3-octave bands are used.

Construction stage. The construction stage is employed during railway track or tunnel construction. This stage is used to enhance the accuracy of model parameters or to validate and adjust predictions made during the planning stage based on site-specific measurements. For instance, when constructing a tunnel, vibration levels in the building can be monitored while drilling and blasting in the tunnel. Such monitoring ensures that vibration limits are not exceeded during construction. These on-site measurements provide valuable information for refining predictions.

2.2. Model

When a train travels underground, it generates vibrations that propagate through the ground and ultimately reach the building, causing elements of the structure to vibrate. The vibration level are influenced by various factors, which are important to consider when developing a prediction model. The prediction of vibration levels on a basement floor is generally formulated as

$$L_{\mathrm{VASmax}} = L_{\mathrm{eASmax}} + \Delta L_{\mathrm{S}} + \Delta L_{\mathrm{g}} + \Delta L_{\mathrm{f}} + \Delta L_{\mathrm{b}} + \Delta L_{\mathrm{corr}} \tag{1}$$

where L_{VASmax} is the A-weighted maximum vibration level using time weighting Slow on a floor in the building (dBA re 50 nm/s), L_{eASmax} is the A-weighted maximum vibration level using time weighting Slow in a reference position (dBA re 50 nm/s), ΔL_{S} is the correction term for train speed (dB), ΔL_{g} is the correction term ΔL_{f} is the correction term for coupling loss at the foundation (dB), ΔL_{b} is the correction term for floor-to-floor attenuation (dB), and ΔL_{corr} is a correction term that may be used to capture various other effects (dB).

The resulting sound pressure in the room is found by

$$L_{\mathrm{pASmax}} = L_{\mathrm{VASmax}} + 10\log_{10}\sigma_S + 10\log_{10}\frac{4S}{A} \tag{2}$$

where L_{pASmax} is the A-weighted maximum sound pressure level using time weighting Slow (dBA re 20 μPa), σ_S is the radiation efficiency (-), S is the area of the radiating surfaces (m^2), and A is the equivalent absorption area of the room (m^2 Sabine).

The model is structured in 1/3-octave bands to account for frequency variations of different phenomena. However, there is no need for frequency dependence to be activated all the time; for example, a single-number level could be used when there is limited information. Single-number levels are suggested in the early stage of location. Moreover, the model is constructed with time-weighting Slow rather than time-weighting Fast since many available models and datasets utilize time-weighting Slow. Time-weighting Slow results in more stable transfer functions.

In buildings, the primary energy of A-weighted ground-borne noise typically falls within 100 Hz to 500 Hz. On the other hand, vibrations in tunnels without A-weighting are mainly low-frequency, below 5 Hz. However, when A-weighting is applied to tunnel vibrations, the most significant levels are observed between 200 Hz and 1 kHz. It focuses on vibrations within the frequency range crucial to ground-borne noise. Consequently, A-weighted vibration levels are used in the suggested model.

2.3. Estimated model uncertainty

Uncertainty estimates have been made for each model term. The uncertainty of the predicted ground-borne noise level is estimated following via a sum of variances of the model terms,

$$u_c^2 = \sum u_i^2 \tag{3}$$

where u_c is the combined standard uncertainty and u_i^2 is the variance of model term i, assuming that a normal distribution can describe the uncertainty of the predicted level. Using two standard deviations (i.e. $2u_c$) is suggested here, defining an interval with a confidence level of approximately 95%.

3. RESULTS AND DISCUSSIONS

In this part, values for each term are estimated for the location and planning stage according to measurements. The model development for construction stage is still in progress and will be published later.

3.1. Source term

The source term represents the vibration level at a specified reference position in a particular direction. In tunnel settings, measuring vibrations on the tunnel wall is generally more feasible. To account for variations in properties along the tunnel and conditions on the bedrock surface, it is recommended to take measurements from a minimum of three positions along the wall. The model suggests using A-weighted maximum vibration levels with time-weighting Slow at the height of roughly 1.5 m above the railhead. The reference distance is defined as 4.2 m. It is suggested to measure vibration in the vertical direction. The vertical direction is the same as the direction of the main forces in wheel-rail interaction. At low and mid frequencies, the whole tunnel moves in the vertical direction, and the vibrations in the horizontal direction are substantially lower. Thus, the vertical direction captures the main vibration energy at lower frequencies.

The source term is formulated as a vertical vibration level at a tunnel wall for a reference track without treatments as

$$L_{\text{eASmax}} = L_{\text{eASmax,train}} + \Delta L_{\text{e,track}} + \Delta L_{\text{e,treatment}} \tag{4}$$

where $L_{\text{eASmax,train}}$ is the A-weighted maximum vibration level using time-weighting Slow at the reference position in the reference direction for the considered train type on the reference track (dBA re 50 nm/s), $\Delta L_{\text{e,track}}$ is the correction term if a track type other than the reference track is used (dB), and $\Delta L_{\mathrm{e,treatment}}$ is a correction term for treatments of the track (e.g. vibration isolation solutions) (dB). The presented source terms are derived from measurements taken on untreated ballasted tracks, which are used as the reference track for this study. There are not sufficient passages of individual train types to obtain precise train-specific source data. Therefore, passenger trains are grouped as one category, and freight trains as another.

Location stage

In the initial phases, typical values for train types and tracks are employed. During the measurements, trains passed at different speeds. The source strength of each passage is adjusted to the reference speed using the speed correction of the Håknäs model (refer to Section 3.2). Subsequently, the arithmetic average of these maximum levels was computed for each train category. The average and standard deviation of maximum levels for various train types measured on the tunnel wall are presented in Table 1. The arithmetic average is chosen as the source term at the location stage. According to the table, the suggested single-number vertical vibration level is 31 dBA (re 50 nm/s) for freight trains and 23 dBA (re 50 nm/s) for passenger trains, with a standard deviation of 4 dB for freight trains and 3 dB for passenger trains.

Table 1: The maximum vibration level for time-weighting Slow on the tunnel wall for various train types, Åsa tunnel average of all positions.

Train types	Direction	Average of maximum levels (dBA)	Average ± 2STD (dBA)
Freight	Vertical	31	31 ± 8
Passenger	Vertical	23	23 ± 6

Planning stage

Figure 1 shows the suggested source term calculated from measurements for the planning stage. It displays the arithmetic average of the spectra of the maximum levels of each passage, as well as the average plus two standard deviations in the 1/3-octave band. The source strength of each passage is adjusted to the reference speed using HS2 speed correction (refer to section 3.2). According to the figure, freight trains generate higher vibration levels than passenger trains.

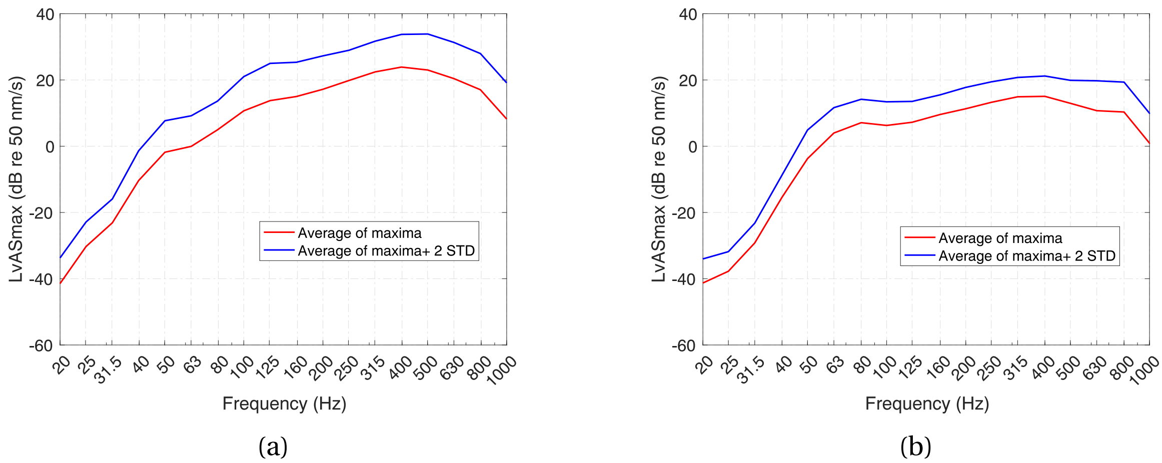

Figure 1: Suggested source strength in the vertical direction, (a) freight train, (b) passenger train.

3.2. Speed term

The speed correction term is used when results are desired at train speeds different from the one used when measuring the reference vibrations.

Location stage

In the preliminary project phases, where data is limited, the Håknäs speed correction model [21] is employed to determine speed adjustments. Based on calculations within the observed speed range, the obtained adjustments closely matched those suggested by the Håknäs model. Equations 5–8, which represent the Håknäs model, are therefore considered suitable for speed correction at the location stage. Here, v is the train speed of interest, and v_{ref} is the reference speed used to determine the source term. The equations propose different speed adjustments for various train speed ranges.

In general, the closer the reference speed is to the calculation speed, the higher accuracy is expected. According to the measurements, the speed range of passenger trains is 120-196 km/h, and the speed range of freight trains is 60-116 km/h. Different reference speeds have been suggested for each category, 90 km/h for freight trains and 160 km/h for passenger trains.

$$\Delta L_{\mathrm{S}} = 20\log_{10}\frac{v}{v_{\mathrm{ref}}} \quad \text{for 80–160 km/h} \tag{5}$$

$$\Delta L_{\mathrm{S}} = 10\log_{10}\frac{v}{v_{\mathrm{ref}}} \quad \text{for 160–240 km/h} \tag{6}$$

$$\Delta L_{\mathrm{S}} = 18\log_{10}\frac{v}{v_{\mathrm{ref}}} \quad \text{for 240–320 km/h} \tag{7}$$

$$\Delta L_{\mathrm{S}} = 0, \quad \text{i.e. constant, above 320 km/h.} \tag{8}$$

Planning stage

As the train speed increases, certain mechanisms related to wheel and rail roughness or parametric excitation lead to a frequency shift upward. This shift may result in energy being transferred into higher 1/3-octave bands. Capturing this frequency shift is crucial for enhancing the precision of the model, as higher frequency bands typically experience greater losses in the ground and exhibit weaker coupling between the ground and the building

In the planning stage, it is recommended to employ a roughness scaling method similar to the one proposed in the HS2 model [22]. By assuming that the only speed-dependent factor is the effective roughness, the vibration spectrum of a train speed v_2 can be estimated by the scaled vibration spectrum at train speed v_1, according to

$$\Delta L_{\mathrm{S}}(f) = R_{\mathrm{eff}}(\lambda, v_2) - R_{\mathrm{eff}}(\lambda, v_1) \tag{9}$$

where $R_{\mathrm{eff}}(\lambda, v)$ is the effective roughness in dB presenting the displacement amplitude resulting from wheel-rail interaction at the wheel-rail interface at train speed v (m/s) and roughness wavelength λ (m). The scaling procedure requires an estimate of the roughness between the wheel and rail, as well as any parametric excitation, such as periodicity in the boogie and sleeper. The speed term uncertainty is calculated based on measurements and presented in Table 2.

3.3. Distance term

It is suggested to calculate distance attenuation considering both geometrical and material damping as follows

$$\Delta L_{\mathrm{g}} = -10\log_{10}\frac{R}{R_{\mathrm{ref}}} - 10\log_{10}\left(e^{-2\pi f \eta (R - R_{\mathrm{ref}})/c_{\mathrm{P}}}\right) \tag{10}$$

where R is the distance from the track, R_{ref} is the reference distance used when determining the source term, η is the material loss factor, and c_{P} is the speed of the pressure wave in the ground.

In the location stage, typical values of the loss factor and the P-wave speed in the bedrock can be used. The wave speed in Swedish bedrock is typically 3000-6000 m/s and has a loss factor of 0.01-0.1. In the planning stage, when more detailed information about the ground property is available, Equation 10 can be used to calculate the exact values.

3.4. Foundation coupling loss term

The foundation coupling loss term describes how vibration transfers from the ground to the foundation and building floor. During the location phase, when adequate information about the foundation is lacking, a conservative assumption is that the ground and the foundation are strongly coupled and vibrational energy is completely transferred. At the planning stage, it is suggested that a coupling loss of 0 dB across all frequencies be adopted. This determination is based on measurement results, which indicate that the coupling loss is around 0 dB across all frequencies. Additionally, a standard deviation of 2.5 dB is calculated for this term, reflecting the variability associated with the measured data.

3.5. Floor term

The floor term represents the alteration in vibration levels as they are transmitted from one floor to another within a multistory structure. The attenuation values for this term typically range from -1 to -4 dB per floor, depending on the type of building. In the absence of specific information regarding each floor above the basement, the recommended default value in the location stage is -1 dB. However, measurement results suggest a potential attenuation of 2 dB per floor, with a standard deviation of 1 dB, particularly for concrete buildings. The same attenuation value is assumed across all 1/3-octave bands during the planning stage.

3.6. Vibration to noise term

As mentioned previously, the maximum sound pressure level for time-weighting Slow in the basement room is derived from various factors. These factors include the maximum vibration levels of the building elements, the radiation efficiency, and the equivalent absorption area of the room. The calculation is based on Equation 2.

At the location stage, when detailed information is lacking, a simplified transfer function can be used to convert vibration levels (dB re 50 nm/s) to sound pressure levels (dB re 20 μPa). The simplified approach assumes a radiation efficiency of 1 (for heavy structures), $T = 0.5$ s for a normally furnished room, floor surface $S = 10$, and adding 3 dB to account for multiple surfaces radiating sound. Equation 2 is then simplified accordingly as

$$L_{\text{pASmax}} \approx L_{\text{VASmax}} + 10 \quad \text{dB}. \tag{11}$$

During the planning stage, if detailed information about specific buildings and their rooms is available, measurements can be made of their dimensions and reverberation times across various frequency bands (1/3-octave bands). These measurements can then be used in the model for more accurate predictions.

A standard deviation of 1 dB is applied to the conversion of vibration to sound pressure level, based on findings by Simmons [23]. Simmons' research suggests that the standard deviation of the term $10\log 10(S/A)$ is approximately 1 dB.

3.7. Uncertainty

The calculated uncertainty for each model term is shown in Table 2. The combined standard uncertainty is computed using Equation 3 and displayed in Table 3. Two times standard deviation is calculated in a single number as well as for each frequency band for both freight train and passenger train. According to table 3, there is more uncertainty in predicting ground-borne noise levels caused by freight trains compared to those caused by passenger trains, especially at lower frequencies (below 50 Hz). One possible reason for this difference in uncertainty is the greater variability associated with freight trains. Factors such as different wagon types, varying loads, and larger spread in maintenance of wheels contribute to higher uncertainty at the source itself for freight trains.

Table 2: Standard deviation of the terms in the prediction model at each frequency (dB).

Frequency (Hz)	Freight source term	Passenger source term	Train speed (freight)	Train speed (passenger)	Distance	Foundation	Floor	Vibration to sound
20	4	3.5	7	6.5	2.5	2.5	1	1
25	4	3	7	5	2.5	2.5	1	1
31.5	3.5	3	7	2.5	2.5	2.5	1	1
40	5	3	6.5	3.5	2.5	2.5	1	1
50	5	4	3	7	2.5	2.5	1	1
63	4.5	4	2	8.5	2.5	2.5	1	1
80	4.5	3.5	3	8	2.5	2.5	1	1
100	5	3.5	3	7	2.5	2.5	1	1
125	5.5	3	3.5	6.5	2.5	2.5	1	1
160	5	3	3	6.5	2.5	2.5	1	1
200	5	3	3.5	5.5	2.5	2.5	1	1
250	4.5	3	3	5	2.5	2.5	1	1
315	4.5	3	3	5	2.5	2.5	1	1
400	5	3	2.5	4	2.5	2.5	1	1
500	5.5	3.5	2	2	2.5	2.5	1	1
630	5.5	4.5	0.5	2	2.5	2.5	1	1
800	5.5	4.5	2.5	2	2.5	2.5	1	1
1000	5.5	4.5	4	1	2.5	2.5	1	1
Single number	4	3	4	2	2.5	2.5	1	1

Table 3: Final uncertainty for the prediction model at each frequency (two times the combined standard uncertainty).

Frequency (Hz)	**Related to freight source (dB)**	**Related to passenger source (dB)**
20	18	16.5
25	18	14
31.5	18	11
40	18.5	12
50	14.5	18
63	13	20
80	13.5	19
100	14.5	17.5
125	15.5	16
160	14.5	16
200	15	14.5
250	13.5	14
315	13.5	14
400	14	12.5
500	14.5	11
630	14	12.5
800	14.5	12.5
1000	16	12
Single number	14	10.5

4. FINAL COMMENTS AND CONCLUSIONS

This study presents a prediction model and methodology for ground-borne noise generated from railways in underground tunnels embedded in bedrock.

A modeling approach is divided into three stages: the location stage, the planning stage, and the construction stage. During the location stage, which represents the initial phase of the project, the model simplifies predictions to a single value. In the planning stage, parameters are defined concerning frequency in 1/3-octave bands from 20 Hz up to 1 kHz, resulting in increased precision compared to the location stage. Finally, in the construction stage, site-specific measurements can be conducted using the tunnel under construction to validate the predictions established in the planning stage.

The prediction model includes a source term and several correction terms. These terms include train speed, distance attenuation, foundation coupling loss, floor attenuation, and the influence of room properties on sound pressure levels within rooms. Furthermore, the model considers the standard deviations associated with each term to estimate the overall uncertainty within the model's predictions.

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